Space VLBI Mission Operational Support at the NASA Deep Space Network

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The first Space Very Long Baseline Interferometry (VLBI) mission VSOP has been successfully operated since 1997 and several follow-on missions are in development or under discussion. The Space VLBI missions are among the most complex space science missions to-date in terms of operations and coordination of the disparate world-wide mission operations elements. In addition to spacecraft operations, nominal to a space mission, overall mission operations include a large ground operations component, including very wideband data acquisition and very high precision frequency/time synchronization and orbit determination/navigation provided by a specialized network of four 11-13 m ground tracking stations around the world, and the "co-observing" support by up to 40 ground radio telescopes around the world. The NASA Deep Space Network (DSN) and the Space VLBI Project Office at JPL are responsible for spacecraft tracking support with the ground tracking station network and for co-observing support with the DSN 70 m ground radio telescopes. This paper will describe the overall Space VLBI mission operations system with particular attention to the mission elements provided by the DSN. The requirements for the support of future missions and necessary improvements to increase the efficiency of mission operations and to decrease mission operations costs will also be described.

1. *Introduction*

The Space Very Long Baseline Interferometry (SVLBI) missions employ a space–based radio telescope operating in conjunction with a network of ground-based telescopes to conduct radio interferometric measurements of celestial radio sources. The observations conducted with such an interferometer could provide high angular resolution images of the radio sources with an unprecedented angular resolution exceeding in orders of magnitude the angular resolution achieved through any other astronomical measurements (e.g., exceeding ~ 100 times the Hubble space telescope angular resolution).

The first Space Very Long Baseline Interferometry (SVLBI) mission - VLBI Space Observatory Program (VSOP) - led by Japan's Institute of Space and Aeronautical Sciences (ISAS) [1] has been successfully operated for more than 3 years. (The VSOP spacecraft - Highly Advanced Laboratory for Communications and Astronomy or HALCA - was launched on February 12, 1997). Several follow-on missions are in development or under discussion. A significant part of the operational support for VSOP is carried out by the NASA's Deep Space Network (DSN) managed by the Jet Propulsion Laboratory (JPL). It is expected that the DSN will play a crucial role in operations support of the future SVLBI missions also.

Aspects of the VSOP mission operations support have been described in numerous papers and technical documentation prior to the launch of VSOP (see for example [2-8]). In this paper, we will describe the principles of the SVLBI mission operations and their realization in the VSOP mission with particular emphasis on the mission operations support provided by the JPL/DSN.

2. *Mission operations requirements for SVLBI*

Relative to other types of space astronomy missions, Space VLBI missions have a set of unique operational requirements. These requirements arise from the nature of the VLBI technique and technology needed to realize the missions. The contemporary Space VLBI missions are characterized by:

1) Need for ground telescopes co-observing simultaneously with the space radio telescope. The current space VLBI project, VSOP, and its successors in the foreseeable future have only one radio telescope in space and heavily rely on co-observing with ground radio telescopes because an interferometer must consist of at least two telescopes to generate the interferometric output and at least three telescopes, and preferably many more, to obtain good quality radio source images. Moreover, since the size of the space radio telescope is relatively small and limited by existing launch capabilities to 8-20 m, the support of the large 70-m class ground-based antennas is crucial to obtaining sufficient sensitivity to be able to observe a statistically valuable sample of radio sources.
2) Very high science data rate (VSOP - 128 Mbit/s) exceeding data rates of most other types of space astronomy missions by two-three orders of magnitude. The detection threshold of a SVLBI

interferometer is proportional to the inverse square root of the frequency band at which the interferometer detects the celestial source signal. Thus, a wider band provides better sensitivity for the interferometer. The frequency bands up to 2-4 GHz wide are envisioned to be utilized for future space VLBI missions. If the radio telescope signal will be digitized at the Nyquist rate with two levels of (amplitude) quantization, such band will correspond to the digital data rate of 4-8 Gbit/s.

3) Need to transmit these data in real time to Earth. The data rate is so high that there is no currently envisioned technology to collect these data onboard during one typical experiment (the duration of a typical experiment is 5-10 hr). The data must be transmitted to the Earth in real time and recorded at the science data acquisition tracking stations. Moreover, the space telescope is only one element in a network of radio telescopes which carry out the VLBI observations simultaneously. Routinely, the number of co-observing ground-based telescopes may be around 10 or more. They record data at the same rate as the tracking stations which receive data from the space radio telescope. Then the data from all the telescopes (including the space telescope) are collected at a special data processing center (correlator) and reduced through correlation and post processing from ~ 10^3 Gbit of raw data to the ~ 10 Mbit of an image. Any gaps in data transmission during the observation (due to a gap in tracking coverage for instance) represents data lost. The duration of the gaps in data transmission is determined by the geometry of the interferometer (spacecraft orbit, orientation of the baseline, location of the ground-based telescopes) and by the availability and location of the data acquisition stations. It is anticipated that such losses of data in the contemporary Space VLBI missions should not be more than 10-20%.
4) Precision frequency/clock synchronization of space based telescope with the ground telescopes supporting the experiment:
1) To obtain successful correlation between the space radio telescope and ground-based telescopes data, the frequency stability of the receiver systems (local oscillators) at each telescope must be an order of $\Delta f/f = 5 \times 10^{-14}$ in a time span of about 100-300 sec – the usual integration time for VLBI experiments. This implies that the hydrogen maser standards at the telescopes are needed as the sources of the reference frequencies. At present it is not technically feasible yet to have an on-board hydrogen maser frequency standard. A two-way radio link with a stable oscillator on the earth is needed to maintain the phase coherence between the space and ground based telescopes.
2) To enable the Earth-to space interferometer to routinely produce the correlation output, the clock difference between the space telescope and ground telescopes must be maintained with an accuracy better than +/- 4 microsecond. Due to the uncertainties in the orbit knowledge and changing position of the spacecraft relative to the ground telescopes, the clock on the spacecraft cannot be accurately set and the clock rate will be changing. The required accuracy of the on-board clock knowledge is achieved through the continuous measuring of the round trip time with the same two-way radio link through which the phase coherency is maintained.
5) Need to provide this frequency/clock synchronization continuously in the course of the observing session. As with the data transmission, breaks in synchronization may result in the degradation of the scientific output of an interferometer.
6) Precision two-way Doppler measurements with a random error of 0.1 mm/s for 1 min count time are crucial to providing the precision orbit determination needed to enable the data processing facilities (correlators) to process/correlate the space telescope data in combination with the ground-based part of the interfereometer.

Thus, in addition to spacecraft operations (including the s/c command control, housekeeping TM monitoring, navigation) and space telescope operations (including control of mode of observations, monitoring of the space telescope systems), nominal to any space astronomy mission, the space VLBI mission operations system is required to support the following functions:

- Real-time high data rate transmission from spacecraft to the ground;
- Continuous frequency/clock synchronization of the space radio telescope and continuous precision two-way Doppler measurements through maintaining a radio link between the ground-based frequency standard and the spacecraft;
- Ground-based telescopes co-observing with the space radio telescope
- Distribution, processing and archiving of the interferometric data;
- Coordination of operation of the multiple mission elements.

3. *Space VLBI Mission operations elements and its functions*

The Space VLBI missions are among the most complex space science missions to-date in terms of mission operations. Such missions are the real champions among space astronomy missions regarding the number of elements involved in support of the earth-to-space interferometer mission operations. Additionally, these missions present numerous challenges associated with the missions' international character since many of the elements supporting the mission operations are distributed world-wide.

Operational support for the Earth-to-Space VLBI missions is executed by the Ground Support System which involves five main components: (1) Science Data Acquisition Tracking network (or "Science" Tracking network), (2) Spacecraft Tracking stations (tracking network) (3) co-observing Ground Telescopes, (4) Data Processing Centers (DPC), and the (5) Orbit Determination System.

1) The content of the ground support system and its functions vary significantly depending on the type of space astronomy mission. Typically, the ground support system consists of a spacecraft tracking network (including tracking stations, spacecraft control center, communication channels) through which the spacecraft and space telescope housekeeping telemetry is received, commands are transmitted, and navigation measurements are executed. The space astronomy missions with relatively low data rates (up to ~ Mbit/s), usually use the same tracking network for science data acquisition by integrating the science data streams with the spacecraft telemetry. But missions with high "raw" data output, like Space VLBI missions, with expected data rates which may be as high as 8 Gbit/s, are forced to use a special "science" tracking network. This network in the Space VLBI missions also functions to provide the transmission of the reference frequency/clock signal from the ground-based standards as well as to use this reference signal for navigational (Doppler) measurements needed for precise orbit determination.

2) The ground-based co-observing radio telescopes are very specific to the contemporary Earth-to-space VLBI missions. Telescopes located around the world are needed to enable the mission and to make it scientifically efficient. These telescopes have to observe at the same observing frequency bands as the space radio telescope. The data recording formats at all co-observing telescopes including space-based have to be compatible to enable the data processing (correlation). The ground-based telescopes have to observe simultaneously with the space-based which imposes a significant coordination problem since most radio telescopes are affiliated with different institutions and have to support other radio astronomy programs.

3) Space VLBI missions have the highest "raw" (observational) data output among space astronomy missions. The initial processing of these data requires a specialized data processor or "correlator." If the VLBI data is not combined in the correlator, these data will not have any value. The correlator processes the "raw" VLBI data (which sometimes may come from up to 20 telescopes as well as from science data acquisition tracking stations which record the space radio telescope data), and reduces the amount of bytes of data by about three to four orders of magnitude. The output of the correlators is then used by the investigator to obtain an image or other astronomical information of the observed radio source.

Data Processing Centers (also called "Correlators") process (correlate) data from the space radio telescope and the co-observing ground telescopes. Along with the initial data reduction, the SVLBI data processing facilities/centers perform data quality analysis, data archiving and dissemination. Historically, the VLBI Correlators maintained the VLBI tape databases and tracked tape movement between the VLBI telescopes and the correlator. For the Space VLBI projects, the Correlators additionally track tape movement between the Science Tracking Network and the correlator. There may be a few Correlators needed to support the mission, since currently a few VLBI data recording formats and media are in use at the VLBI telescopes. Also, the existing VLBI Correlators like ground-based telescopes have to share the operational resources between many projects besides processing the SVLBI data.

4) The Orbit Determination System provides the information needed by the spacecraft and science tracking stations for communication with the spacecraft and the orbital information needed for data processing. These data are calculated based on the navigation measurements from both the spacecraft tracking stations (Doppler and range) and science data acquisition network (Doppler).

The Mission Operations System (MOS) is a conglomerate of operations facilities, computer hardware and software, and personnel. The MOS performs planning, resource allocation, mission element performance monitoring and analysis, commanding, and archiving of the mission operations data. The major responsibility of the MOS is to provide safe and reliable spacecraft operations (including the spacecraft service bus and science payload/telescope). In order to do this, the mission operations system coordinates, plans and allocates the mission resources including spacecraft power, fuel for orbit and attitude corrections, and the time needed by the ground-based tracking network to track the spacecraft.

Table 1. The VSOP SVLBI mission operations support structure

SVLBI Mission Operations elements		*VSOP element(s)*	*Function(s) /Realization*	*Affiliation/Location*
Ground Support System	"Science" Tracking network	Orbiting VLBI network with five Ground Tracking Stations (GTSs);	1) Provide: a) science data acquisition, b) on-board frequency / clock synchronization, c) orbit (Doppler) measurements; 2) K-u band (~15 GHz) channel is used for data and reference signal transmission; SRT data are recorded in VLBA and S-2 formats	1) Three NASA DSN 11-m antennas, one of each located in Goldstone, (USA), Canberra (Australia), Madrid (Spain); 2) 14-m NRAO antenna in Green Bank (USA); 3) 10m ISAS antenna in Usuda (Japan)
	Ground Telescopes	About 40 Ground-Radio Telescopes (GRTs)	1) Provide co-observation with space radio telescope; 2) Telescopes co-observes in two bands: L (1.6 –1.7GHz) and C (~ 5 GHz) ; Data are recorded in four VLBI data formats: MKIV, VLBA, S-2, K-4	These telescopes are affiliated with radio astronomy institutions from ~ 17 countries and the VLBI networks, including the VLBA, EVN, and NASA's DSN (70-m subnet) have committed up to 20% of their time to support SVLBI observations.
	Data Processing Centers (Correlator)	Three Correlators	1) Provide SVLBI data correlation, data tape logistics, data archiving; 2) VLBA, S-2, VSOP Correlators process the data in MKIV/VLBA, S-2 and K-4 formats, respectively;	1) VLBA Correlator (NRAO, USA) 2) VSOP Correlator (NAO, Japan) 3) S-2 Correlator (HIA, Canada)
	Spacecraft Tracking station(s)	-Spacecraft operations station in Kashima; -26 m DSN subnet	1) Spacecraft / telescope control, monitoring, orbit measurements; 2) S-band (2.2-2.3 GHz) channel is used for communication	1) Spacecraft operations are conducted from Kashima Space Center (Japan); 2) NASA DSN 26 m subnet provides navigation and TM support outside of the Kashima station's view in case of a spacecraft emergency;
	Orbit Determination System	Two Orbit Determination centers	Provide orbit parameters to support the spacecraft operations (NASDA) and mission data processing (MMNAV)	1)The NASDA (Japan) provides s/c navigation support; 2)MMNAV system of JPL (USA) provides orbits for data processing
Mission Operations System		VSOG	Coordinate overall mission operations including spacecraft and ground support systems	Located in ISAS (Japan); the group membership is international.
		DOTS	Coordinate and monitor operations of the OVLBI network	Located in JPL(USA); managed by the US Space VLBI Project
		GBES operations	Support the GBES tracking station operations	Located in Green Bank, USA; managed by the NRAO's Space VLBI Project
		GRTs operations	Ground telescopes and networks operations	Operations are conducted by teams of operators located at the telescopes sites or network operations centers
		Correlators operations	Support Correlator operations	Operations are conducted by the Correlators operations teams
Science Operations System		Science Review Committee	Conduct scientific peer review and ranking of proposals	International membership;
		Science support groups	Analyze the interferometer data output and propose the ways to optimize it	1) Data analysts at the correlators; 2) JPL SVLBI Project Science team; 3) VSOP Data Reduction group;
		Principle Investigator	Propose the experiments and observing programs	Open to any qualified scientist from around the world.

Abbreviations: VSOG – VSOP Science Operations Group, DOTS - Data Oversight and Transfer System, GBES – Green Bank OVLBI Earth Station, VLBA – Very Long Baseline Array, EVN – European VLBI Network, NRAO – National Radio Astronomy Observatory (USA), NAO – Nobeyama Astronomical Observatory (Japan), HIA – Herzberg Institute for Astrophysics (Canada), NASDA – National Space Development Agency (Japan), MMNAV – Multimission Navigation.

The space astronomy missions like Earth-to-space VLBI (VSOP) which operate as open observatories which any qualified scientist can use for observations if his proposal is accepted, usually establish a specific "science operations" system. This system oversees science planning, allocates the mission/telescope observing resources, monitors the quality of the science output, and archives the science data. One of the tasks of the science operations system is, in the event of a space telescope malfunction, to evaluate the observing capabilities and performance of the space telescope and to inform the proposers of changes to the telescope's configuration. Even during normal, routine operations of an Space VLBI mission, a significant amount of simulations are needed in order to evaluate the right configuration of the space- and ground-based telescopes, the appropriate observing date for a given source, etc. This is also the task of the science operations system. This and other science operations functions are conducted by the mission's science operations and support groups. (The "science operations" system may be considered as the subsystem of mission operations. It was distinguished here from mission operations since it uses separate facilities and groups of people to perform the specific tasks.)

The mission operations structure and functions of its elements may vary depending on the available resources and the rules of the agencies which participate in the mission. The form of the mission operations in the VSOP mission is shown in Table 1. It is worth noticing the diversity and number of the VLBI recording data formats (four) and number of Correlators (three) involved. It is evidently not an optimal configuration because the use of multiple formats and facilities significantly complicates the mission operations. The mission inherited this diversity with the need to involve as much as possible ground-based radio telescopes to support the mission operations. Historically, the radio telescopes in different parts of the world used different VLBI systems. This compatibility problem was resolved by using subnets of telescopes operating in the same format and by using the special processor at the VSOP correlator which converts the data from different VLBI formats to each other. Also, the use of the DSN 26 m subnet, which was not in the original mission design, proved to be very useful for navigation measurements and TM reception outside of the Japanese Kashima station's view in case of a spacecraft emergency.

4. Space VLBI mission operations (data flow)

The mission elements interact with each other through information and/or product exchanges. There are basically two types of information exchanged - control (including plans, schedules, commands) and data (data files containing the spacecraft and telescope health information, science data, etc.).

Figure 1 represents the generic diagram of the vital data and control information flows in an Earth-to-space VLBI mission. (In order to simplify the diagram, we assumed that all ground elements are operating nominally and are available for mission support. If one of the mission elements has operational problems, it will report the anomaly to the mission or science operations team and repair the problem with its own resources. In the following text, the mission element data products are in *italic*).

The *Science Data* (Science Telemetry) from the space radio telescope are transmitted from the spacecraft and recorded on tapes at the tracking stations and sent directly to the Data Processing Center (DPC). The *Space Radio Telescope Auxiliary Data* containing the data time-tag information ("Time Correction File"), space telescope LOG (the records of events at the telescope during the observations) and other information are transferred through the internet from the network stations to the network operations center where it is stored on an internet server for retrieval by other mission elements, including the DPC. *Navigational Measurements* in the form of Doppler measurements in the reference frequency link channel is also transmitted through the internet from the tracking stations to the network operations center from where it can be retrieved by the Orbit Determination System (ODS). In order to function, the Science Data Acquisition Tracking network must receive the *Schedule* from the Mission Operations System and spacecraft *Tracking Predicts* (spacecraft orbit information and Doppler predicts needed for the communication channel).

Scheduling of the ground telescopes for co-observations is done by the SVLBI mission Science Operations System in a manner compatible with routine VLBI network operations. Long-term observing *Plans* are agreed to well in advance but may be corrected in accordance with the current status of the spacecraft and other mission elements. The actual *Schedule* files (electronic files which define the observing sequence and procedures) are distributed to the co-observing telescopes two weeks in advance of the observation. The *Science Data* tapes and *Auxiliary Data* from telescopes are delivered to the data processing centers for correlation.

All data required for correlation must be received at the respective correlator no more than 2 weeks after the observations are made. The *Science Data* tapes from the telescopes and science tracking stations are received by mail, while all the telescope supporting *Auxiliary Data* are sent electronically to the internet servers maintained at the Data Processing Centers. The space radio telescope *Auxiliary Data* (including the telescope LOG and time correction file) are retrieved by the correlator from the internet server maintained at the Science Tracking Network Operations Center. This strict requirement on the data delivery timeline is very important. Because the number of data tapes available for VLBI operations are limited (they are very expensive ~ \$1000 per tape on which about 12-24 hours of observations – one experiment – are recorded) and the data correllation takes approximately the same amount of time as the experiment, data processing delays at the correlators may lead to the absence of tapes for data recording at the telescopes or tracking stations and, accordingly, to the loss of data. In order to correlate the data, which comes on the tapes, the Data Processing Centers must know the spacecraft's orbit at the moment the observations were made with a high accuracy. This "*Reconstructed Orbit*", the set of orbit parameters generated after the observing session using the navigational measurements which were made before and during the observations, is provided electronically to the DPCs by the Orbit Determination System according to the same timeline as the data tape delivery.

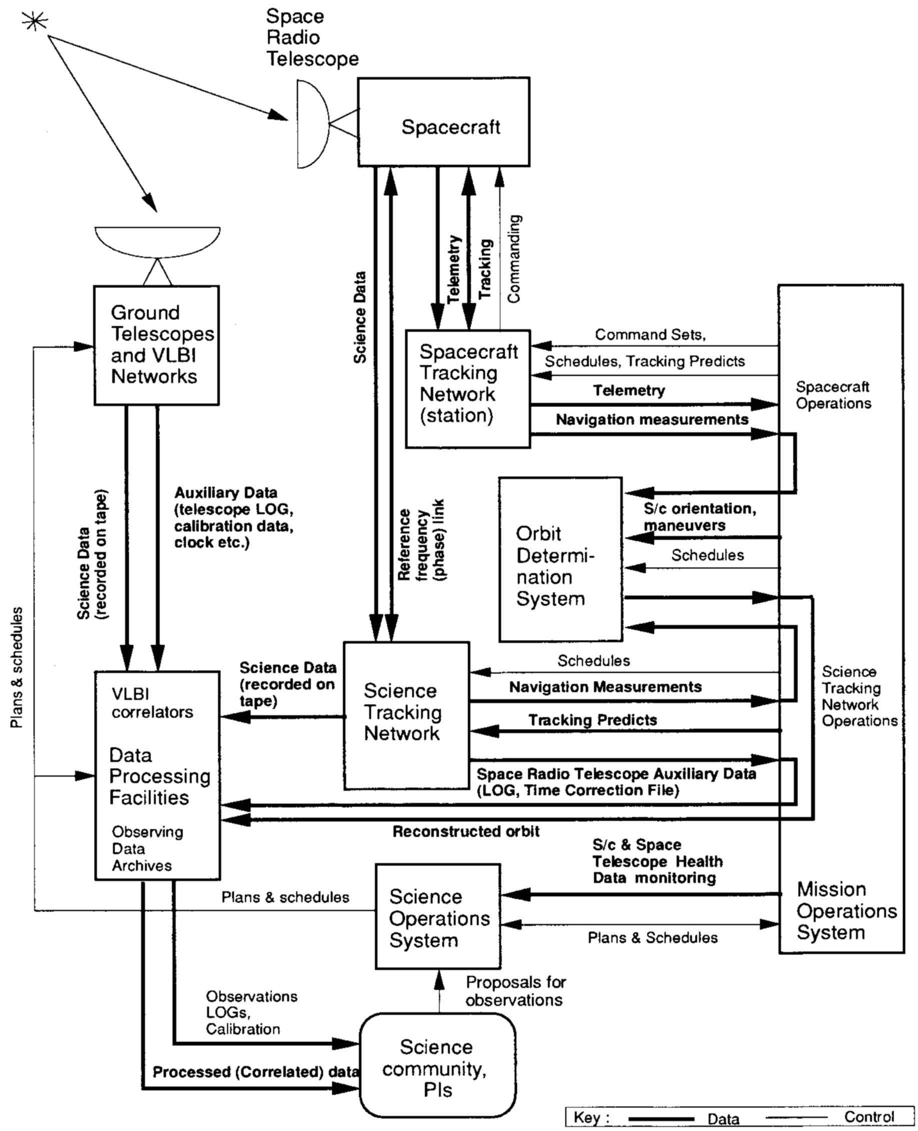


Figure 1. Earth-to-space VLBI mission operations data flows

The control and monitoring of the spacecraft and space radio telescope are executed through the spacecraft tracking station or network of stations. The spacecraft tracking network (1) executes *Commanding*, (2) provides *Navigational Measurements* by way of measuring the spacecraft distance and velocity (Doppler) through transmitting and receiving a radio signal, and (3) receives the spacecraft and space radio telescope *Telemetry* and transfers these data to the orbit determination system and to spacecraft operations. To perform this function, the spacecraft tracking network must receive the *Schedules*, *Command Sets* and *Tracking Predicts* from the mission operations group. Since observations with the onboard telescope in the VSOP project are executed mostly in the spacecraft autonomous operations mode, the spacecraft tracking station communicates with the spacecraft only during a small part of each orbit. The VSOP spacecraft is using a communication channel for spacecraft operations which is different from the science data and reference frequency transfer communication channels (see Table 1). The separation of these two channels (different frequencies, different onboard antennas and radio complexes, etc.) provides the redundancy which can help to restore spacecraft functioning in the case of an emergency situation onboard the spacecraft. To provide even more safety for the mission, the spacecraft and the space radio telescope monitoring data are included in the *Science Data* flow which is received by the science tracking network and then delivered to mission operations.

The Orbit Determination System receives the *Navigation Measurements* from both the spacecraft tracking stations and science tracking network. It generates the *Tracking Predicts* – information needed by the spacecraft and science tracking stations to point to the spacecraft and adjust the communication frequencies due to the Doppler effect from spacecraft motion – and the *Reconstructed Orbit* for data processing. In order to generate a highly accurate *Reconstructed Orbit*, additional information on the spacecraft's attitude and maneuvers is required. The significant mechanical forces (drag) generated due to the interaction of the large parabolic antenna of the space radio telescope with the atmosphere near the orbit perigee and with the solar wind have to be accounted for the orbit reconstruction by way of mathematical modeling.

The request for an observation comes in the form of a *Proposal* from a Principle Investigator which, before the observation can be carried out, is reviewed and evaluated by the mission Science Program Committee. The mission's science operations system evaluates the technical visibility of the proposal in accordance with the current status of the mission systems. In order to do this, the Science Operations Group needs to know the status of both the space radio telescope and spacecraft systems. The *Spacecraft and Space Radio Telescope Health Data* are supplied by the Mission Operations System. Based on this information the "Science Operations" and Mission Operations Systems negotiate the long-term (duration about 1 year), mid-term (duration 3-4 months) and short-term observing *Schedules/Plans* for the spacecraft and space telescope operations. The "Science Operations" System also generates the Plans and Schedules for the Ground Telescopes and the VLBI correlators.

Finally, when the observations are completed and processed at the VLBI correlator, the *Correlated Data* as well as the *Observations LOGs and Data Calibration* files are delivered to the Principle Investigator of the experiment from the Data Processing Centers. The Principle Investigator is responsible for the observation's final product – the analysis and publication of results. The usual practice is that during the first 6 months to 1 year after the experiment, the Principle Investigator has sole access to the data for analysis and publication. After this period, the data becomes available for analysis by the astronomical community at large.

The Space VLBI Mission/Science Operations heavily rely on the Internet. Most of the mission operations information products, except the VLBI data itself, are distributed through the internet. The need to reduce the cost of a mission has led to the use of distributed data archives, especially for the intermediate mission operations products. For example, in the VSOP SVLBI mission, the mission operations products (schedules, auxiliary data files, spacecraft and space telescope records of events, etc.) are stored on internet servers maintained by the respective mission element. If some mission element (e.g., Data Processing Center) needs spacecraft orbit data, or space telescope records of events, the needed information can be downloaded from the relevant server via the internet. Most of this information is needed only for mission support and is not needed for the Principle Investigators of the experiments who are interested only in their experiment results. Thus, the access to these servers where the mission operations products are stored is restricted. Nevertheless, in the case of a problem with data processing or interpretation, these auxiliary data may be revisited and obtained directly from the archives of the mission elements.

5. *JPL/DSN segment of the VSOP mission operations*

The overall management of the VSOP mission operations support in the JPL DSN is carried out by the US Space VLBI Project Office. The JPL/DSN resources dedicated for the VSOP mission operations support include: 1) 11m DSN subnet - three from five tracking stations supporting the VSOP science data acquisition and frequency/clock reference link; 2) Data Oversight and Transfer System (DOTS) - computers/software and a team of mission operators responsible for delivery of tracking and telemetry data from the DSN tracking stations to the other mission operations elements, as well as generation and delivery of schedule files for those stations, end-to-end validation of the scientific telemetry, and planning and implementation of the day-to-day mission operations; 3) US SVLBI Project Science Team which makes certain that the final scientific products of the mission (the quasar images) are of the highest quality through the evaluation of the scientific data and optimization of the planning of scientific observations with the VSOP.

Other JPL/DSN resources involved in the VSOP operations support are: a) DSN's Multimission Navigation system provides the navigation support for the mission based on the trajectory measurements made with 11 m subnet and 26 m DSN subnet (former in case of a spacecraft emergency), b) DSN 70 m antennas conduct the co-observing observations with the space radio telescope on a non-interference basis with the support of the other DSN flight missions. The 11-m and 70-m DSN subnets operations as well as the VSOP navigation support by MMNAV are carried out by the JPL's Tracking and Mission Operations Directorate for the US SVLBI project.

The external and internal interfaces and data flow in the US SVLBI Project's VSOP mission operations segment are described in Table 2.

Table 2. US SVLBI Project's VSOP mission operations segment

Mission operations element	*Input*	*Output/Product*	*User*
DOTS	1) SRT Schedule file 2) *Monitor Data* 3) *Tracking Data* 4) Station LOG's 5) DSN Frequency and Time system Report 6) Predicted Orbit 7) Reconstructed Orbit	*"up-link" products*	
		DSN Schedule file	11-m DSN
		Predicted Orbit file	11-m DSN, GBES
		"down-link" products	
		Time Correction file	Correlators
		Reconstructed Orbit	Correlators
		Station Status Report	VSOG
		Station LOGs (performance, S-2, VLBA)	VSOG
		Telemetry Header file	VSOG
		Station Monitor Data file	VSOG
11-m DSN subnet	1)DSN Schedule file 2) Predicted Orbit file 3) Data link signal 4) Frequency/clock synchronization link signal	Space radio telescope science data on VLBI tapes VLBA or S-2 formats	DOTS, MMNAV
		Tracking data (Time Difference File, Phase Residual File)	DOTS
		Station Monitor Data file	DOTS
		Telemetry Header file	
		Station LOG's (events, S-2, VLBA)	
MMNAV	11-m tracking data	Predicted Orbit	DOTS
		Reconstructed Orbit	
70 – m DSN subnet	1) GRT schedule file 2) Radio source signal	Science data on VLBI tapes	Correlators
		Telescope calibration and LOG files	
Project Science Team	1)Predicted orbit 2) Correlated SVLBI data (test experiments)	Optimized long-term observation schedule	VSOG
		Monitoring of the SVLBI interferometer performance	

5.1 US Space VLBI Project mission operations

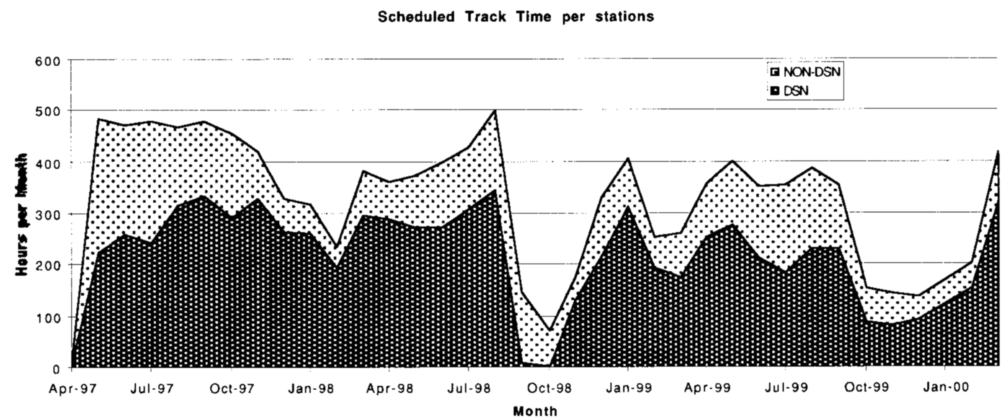
The coordination of the VSOP mission operations is executed through scheduling. Based on the information on the status of the Space Radio Telescope (SRT) and status and availability of the mission operations elements, the VSOG generates SRT and GRT schedule files which contain the information needed to conduct the communication sessions between the 11m tracking stations and the spacecraft and conduct the co-observing at the ground telescopes, respectively. The DOTS automatically retrieve the SRT file from the VSOG internet server, which is located in Japan every 15 minutes. Similarly the ground radio telescopes retrieve the schedule files from a few designated VLBI servers located in the radio astronomy organizations around the world (regional servers) at which the VSOG places the file. The DSN 70m subnet retrieves its schedule file from the VLBA/NRAO server in Soccoro, NM.

The DOTS at JPL serves as the centralized interface point between the VSOP mission Science Operations Group (VSOG) and the DSN 11-m tracking network. Input products to the DOTS are from the network and its specifications are governed by the interface agreements between the US SVLBI project and DSN. The output products of DOTS are governed by interface agreements with other VSOP mission elements. The logical flow of data may be divided into `up-link' and `down-link' stages, where `up-link' refers to the scheduling of the DSN tracking stations, resulting in Space VLBI satellite tracking, signal acquisition and VLBI recording, and where `down-link' refers to the results of a particular VSOP satellite tracking pass. The DOTS computer are running a few programs which process the input data and generate the output files (Time Correction File, TCF, and Telemetry Header File, THF) needed by the Correlators and VSOG. (The TCF is used by Correlators to correct the time-stamps of digitized space radio telescope data recorded at the tracking stations to enable the SVLBI data correlation; the THF contains the spacecraft telemetry and used by the VSOG for spacecraft health monitoring). The downlink products are stored at the DOTS internet server from where they are retrieved by the Correlators and VSOG.

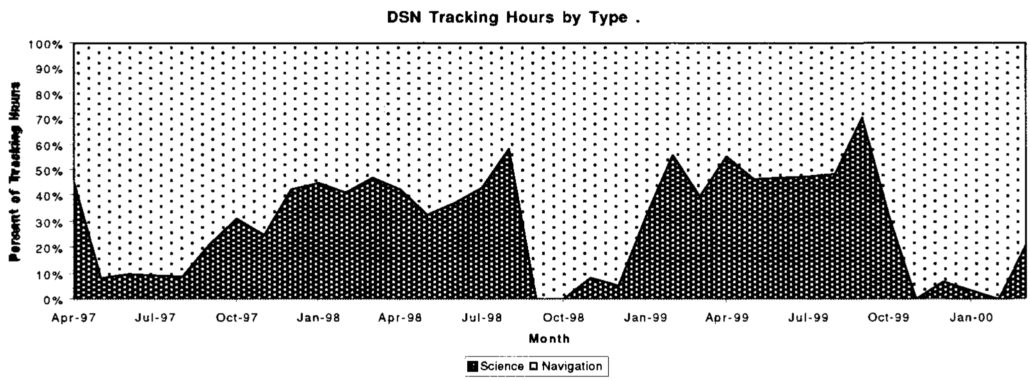
DSN 11-m tracking stations receive the DSN schedule and station configuration files generated at the DOTS through the DSN Network Scheduling Subsystem (NSS) once a week. They conduct the communication sessions with spacecraft according to the schedule producing the tapes with science data recorded in two VLBI formats depending on the configuration of space VLBI experiment (the co-observing telescopes must record their data in the same format) and a set of tracking measurements, and LOG files, which then are delivered to the DOTS through internet in 'near-real-time' (in Table 2 shown in *italic*) or 'post-pass'. The tracking measurements are also delivered to the JPL's Multimission Navigation to generate the Predicted and Reconstructed Orbit files.

The DSN's Multimission Navigation system supplies the predicted orbit for the DSN 11 m tracking network and Green Bank (GBES/NRAO) tracking station once a week. These predicts are used for antenna pointing and frequency Doppler shift predictions. The highly accurate Reconstructed orbit for a period of 7 days derived from the results of tracking measurements and made available for Correlators once a week.

The data flow from the stations to DOTS as well as the metrics of the 11-m subnet performance are monitored through the US SVLBI Project mission operations system website on the internet. The history of the DSN 11- m subnet operations is shown in Figure 2a. In average, the DSN support accounts for more than 70% of the operational time of the VSOP mission. There are two types of the tracking passes performed by the DSN subnet: "Navigation", which purpose is to obtain the tracking measurements (Phase Residual) for spacecraft navigation, and "Science" - the tracks at which the science data from the space radio telescope were acquired along with navigation measurements (see Figure 2b.) The low number of the science passes indicates the periods when the spacecraft was non-operational.



2 a)



2 b)

Figure 2. History of the VSOP operations support by the DSN 11m antennas

The performance of the 11-m DSN subnet is crucial for the success of the mission. A set of metrics was developed to monitor its performance. Figure 3 depicts the history of the subnet performance in terms of Percent Data Valid (PDV) metric. Although at the beginning of the mission the performance of the stations were not very good, by the end of the mission's in-obit check out period (third quarter of 1997) it was significantly improved with ~ 50% of the passes having PDV >95%. (The project requirements for mission support is a PDV of > 95%). Due to the significant efforts of the project and the DSN personnel the performance of the network has gradually improved reaching about 70 - 80% of tracks which meet or exceed the requirements (PDV> 95%).

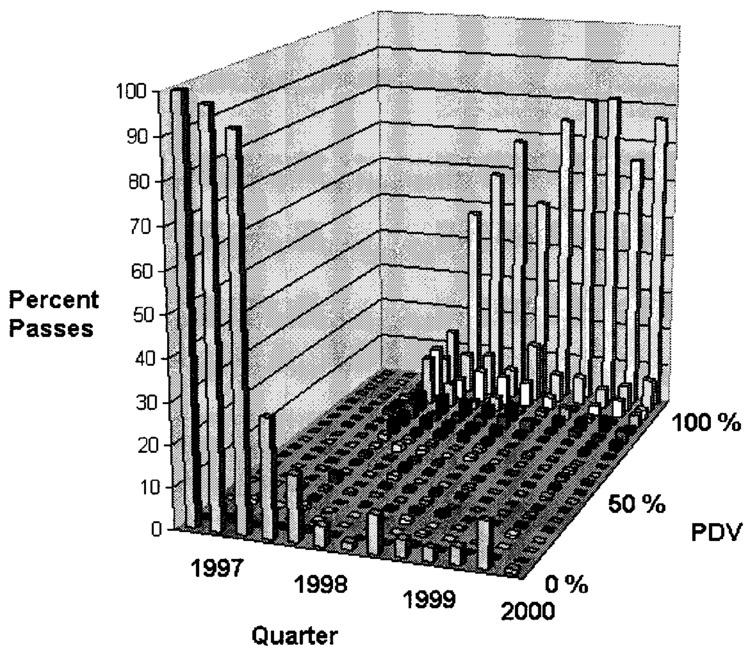


Figure 3. History of the DSN 11m network performance

The high quality navigation support provided by the JPL's MMNAV system have been crucial to the success of the mission. The accuracy of the Predicted and Reconstructed orbit solutions provided by the MMNAV exceeded the requirements which significantly simplifies the spacecraft and Correlators operations.

5.2. DSN 70-m co-observing and mission science operations

The DSN 70-m antennas are participating in the SVLBI co-observing along with other ground-based telescopes around the world. The DSN supported observations at one (L-band) from two (L and C-band) of the VSOP operational bands. By the end of 1999, the L-band experiments accounted for about 20 % of the VSOP program. The DSN time was allocated for co-observing on a non-interference basis with other flight projects supported by the DSN. Despite this, DSN L-band co-observing support was provided for more than 60% of the VSOP L-band observations (see Figure 4). It also shows the importance of the large 70m antennas for the SVLBI mission (a majority of the ground-based telescopes which participated in co-observing with VSOP were 25-m size class).

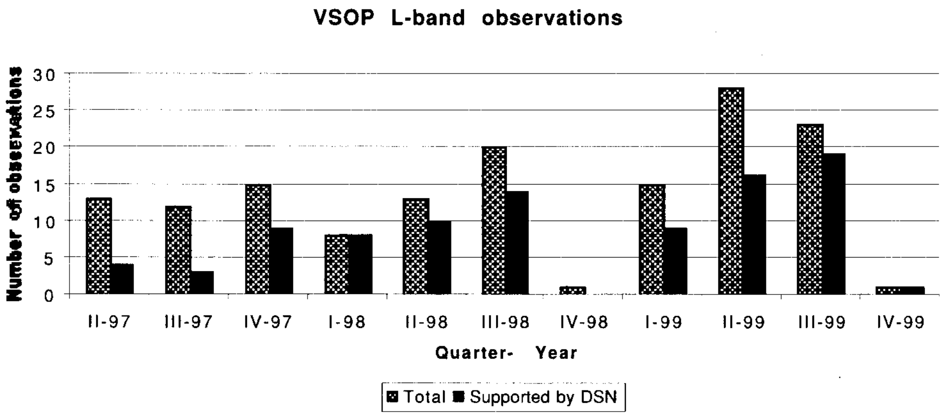


Figure 4.

The performance history of the DSN 70-m antennas in terms of the Percent Data Delivery metric (ratio of the duration of a radio source signal recorded to the time requested by the VSOP project) is given in Figure 5.

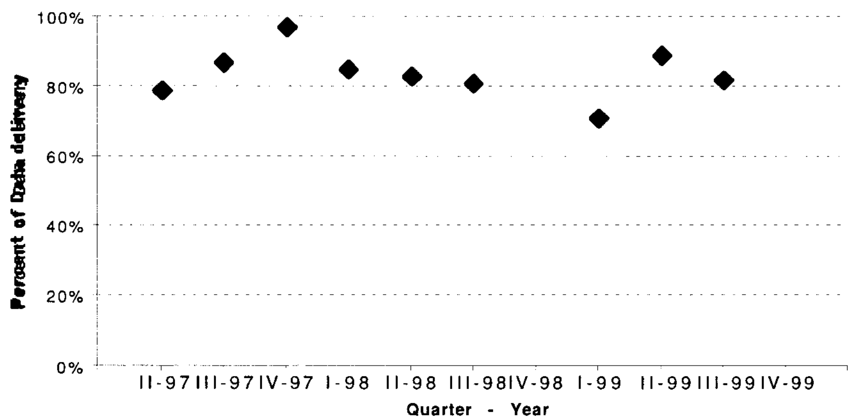


Figure 5. DSN 70-m SVLBI co-observing performance

The JPL SVLBI Project Science team provided significant input in two areas of the VSOP mission operations: 1) two packages of the simulation and scheduling software were developed [7,8], which were extensively used during the mission for long term planning and scheduling of the experiments, and 2) assistance was provided in evaluation of the scientific output depending on the Earth-to space interferometer configuration. The example of the output product of the simulation software is given in Figure 6. Such plots representing a graphical evaluation of the quality of the image of radio sources depending on the their positions in the sky, spacecraft orbit and configuration of the ground telescope network supporting experiment have been routinely used for the mission operations planning. The "Sky plot" is showing the zone of avoidance (~80 deg around the Sun) at which experiment planners (PIs) must not chouse the target for observation at this period of time and the "UV coverage"(the track of the projection of the interferometer baseline on the sky while the orbiting telescope is moving in its orbit) which characterizes the quality of the image which can be obtained depending on the position of the source in the sky (more dense picture – better quality).

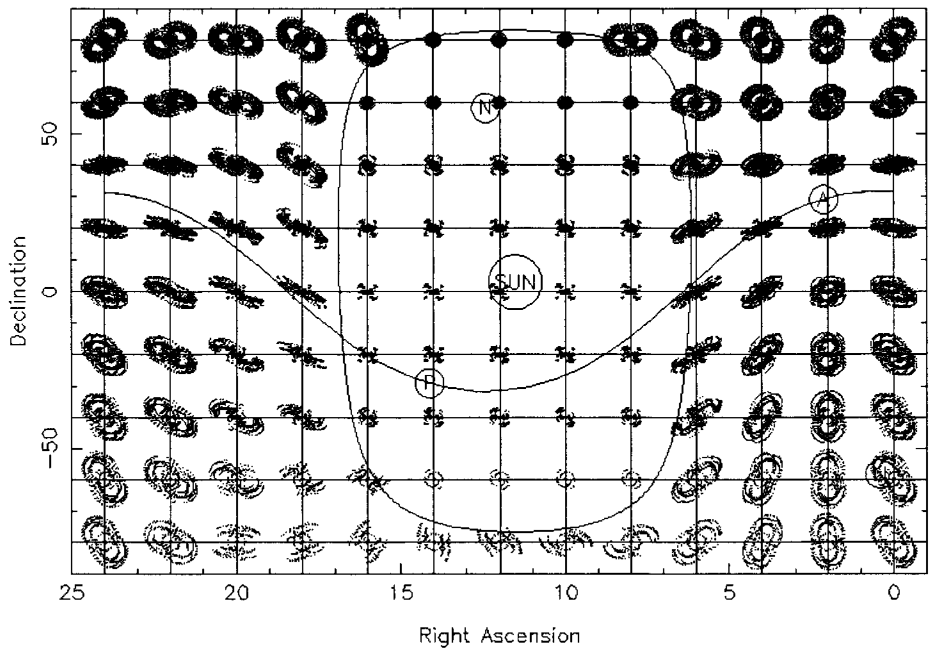


Figure 6. Sky plot for the chosen earth-to-space interferometer configuration in September 2001

5.3 Project special operations

A number of mission critical events have been supported by the US SVLBI Project besides the routine operations in support of the VSOP mission.

Although the technique of frequency/clock synchronization through a radio link with the spacecraft was tested in the first earth-to-space VLBI experiments with the TDRSS satellite [9] (performed in the mid 1980s), implementation of the technique at the DSN tracking stations must be verified. A set of extensive tests with the special satellite, SURFSAT, built by the US SVLBI project which carries on board a transponder imitating the VSOP satellite, was performed prior to the launch of VSOP [10]. The test successfully demonstrated the readiness of the frequency/clock synchronization system at the DSN tracking stations.

The VSOP mission in-orbit check out continued for 6 months after launch. The check out of the end –to-end performance of the earth to-space interferometer with the involvement of the OVLBI tracking network and ground-based telescopes began about 1.5 months after launch after the space antenna was deployed and the spacecraft check out was completed. The 11m DSN subnet and DOTS supported the mission operations from the very beginning. Despite intensive pre-launch testing, the final tuning of the system (adjusting the science telemetry and frequency/clock synchronization systems) took a significant amount of time (~ 4 months, see Figure 3).

During its 3 years of operations, the HALCA spacecraft had a few emergency events which caused an interruption in observations lasting for a few months. During these periods, the NASA DSN provided additional support with the DSN 26-m subnet operating in S-band - the VSOP spacecraft's communication channel. The 26m DSN sunbnet support, including navigation measurements and spacecraft TM in S-band, proved to be crucial for successful recovery of the spacecraft. The DSN subnet tracked the spacecraft during the periods when it was not visible from the main spacecraft tracking station in Kashima. The results of the tracking were immediately made available by DOTS to the VSOP mission operations. The extended tracking coverage helped to determine the spacecraft status and maintain navigation which ultimately shortened the non- operational periods, and thus, increased mission efficiency.

6. *DSN operational support for future SVLBI missions*

The JPL/DSN Space VLBI mission operations segment (including 11-m subnet, DOTS) was designed and built to support two missions VSOP (Japan) and Radioastron (Russia). Although the Radioastron mission launch has been delayed, the development of the spacecraft and space radio telescope for the mission have significantly advanced in the last few years, and there is hope that the mission will be launched in the next two-three years. Aspects of the Radioastron mission operations are described in references [11-12]. The prime differences between VSOP and Radioastron which determine the differences in the mission operations are: 1) a different orbit, 2) different communication channels for science data acquisition and frequency/clock synchronization, 3) a different set of observing wavelengths and possible space radio telescope observing modes. All elements of the JPL/DSN Space VLBI mission operations segment are capable of supporting the Radioastron mission.

A few next-generation Space VLBI missions are under consideration within different space agencies [13,14]. These missions plan to have significantly larger data rates (up to 8 Gbit/s is envisioned) and observe at higher frequencies (up to 86 GHz) to realize higher sensitivity and higher angular resolutions. The higher data rates will require a significant upgrade of the data link electronics, including changes to support this link at higher frequency bands, Ka (37-38 GHz) and W (74-84 GHz), allocated to the Space Research Service to accommodate a few Gbit/s data streams. The ground-based telescopes with large (~ 25-30-m class) high-precision apertures capable of operating at millimeter wavelengths will be needed to provide sufficient sensitivity of the earth - to-space interferometer. It is essential for decreasing of the mission operations cost that the tracking and co-observing support operations for future space VLBI will be automated (unattended by operations personnel) as much as possible.

The JPL/DSN is uniquely suited to support the next generation Space VLBI missions. NASA's deep space communication is currently evolving to exploit the Ka–band which will provide the technology needed to develop the required wide-band communication channels. The DSN 34-m class antennas are capable of effectively operating up to 100 GHz thus providing the opportunity to support co-observing with the future SVLBI missions. In the course of preparing and operating the VSOP mission, the DOTS and DSN 11-m subnet operations have been significantly automated providing the experience for upgrading to support future missions. The operations tools and knowledge which were developed will help effectively operate the future SVLBI systems.

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